MEASUREMENTS OF COSMIC RAYS WITH PRIMARY ENERGIES UP TO 10^{20} eV

Recent results from the Pierre Auger Observatory

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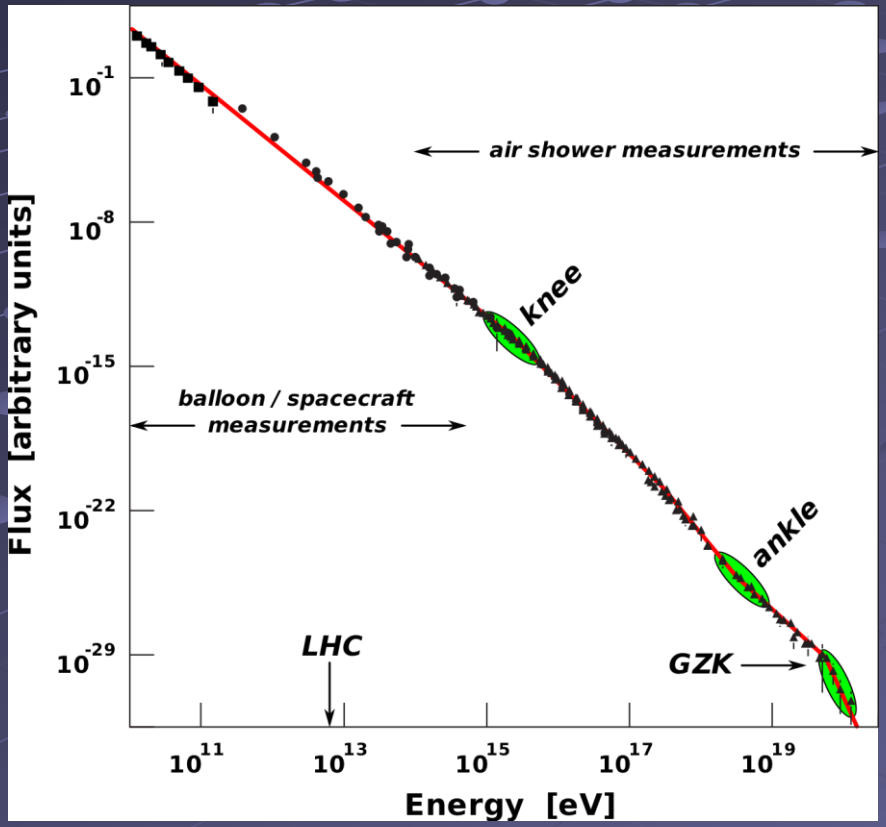
Wien, May 25, 2010

OUTLINE

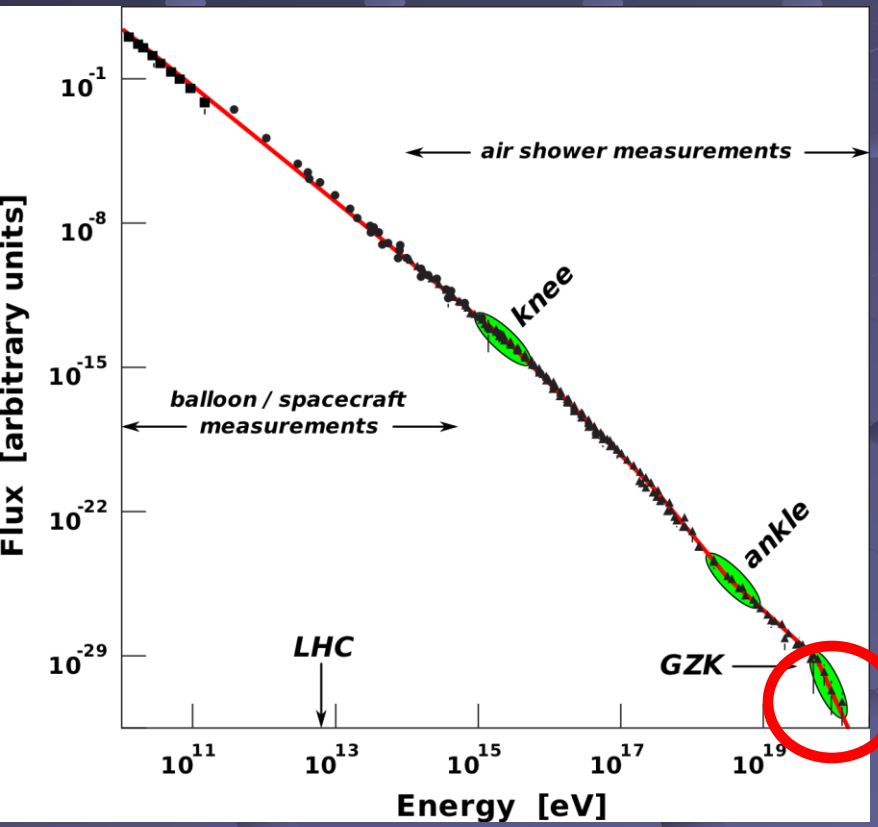
- Brief overview of UHECR
- P. Auger Observatory
  - Experimental method
  - Results
    - Spectrum
    - Composition
    - Photon flux
    - Arrival direction
- Conclusions

WHY STUDY UHECRs?



- Measured spectrum extends to $E > 10^{20}$ eV
- Where and how are cosmic rays accelerated to these energies
- No known astrophysical sources seem able to produce such enormous energies
- Chemical composition unknown
- The high energy end of the spectrum probes physics at energies out of reach of any man made accelerator
- Possible new physics

WHY STUDY UHECRs?



Accesible to experiment

- Energy spectrum
- Chemical composition
- Arrival directions

Astronomy with charged particles?

Problems

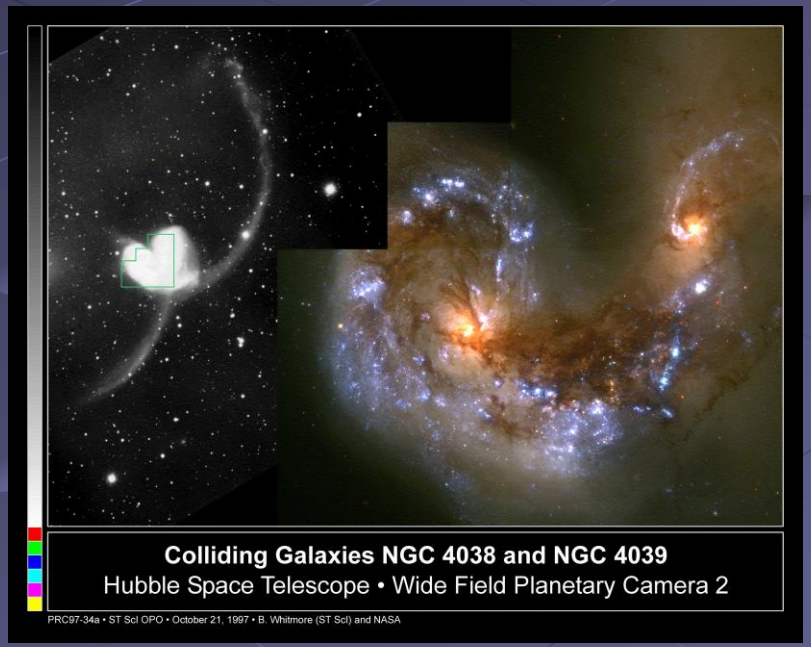
- Very low rates call for giant observatory
- Protons and nuclei are charged and therefore deflected by galactic and intergalactic magnetic fields

← 1 particle/km^2/century or a few particles/km^2/millenium

POSSIBLE SOURCES

Bottom – Up (Astrophysical Acceleration Mechanisms)

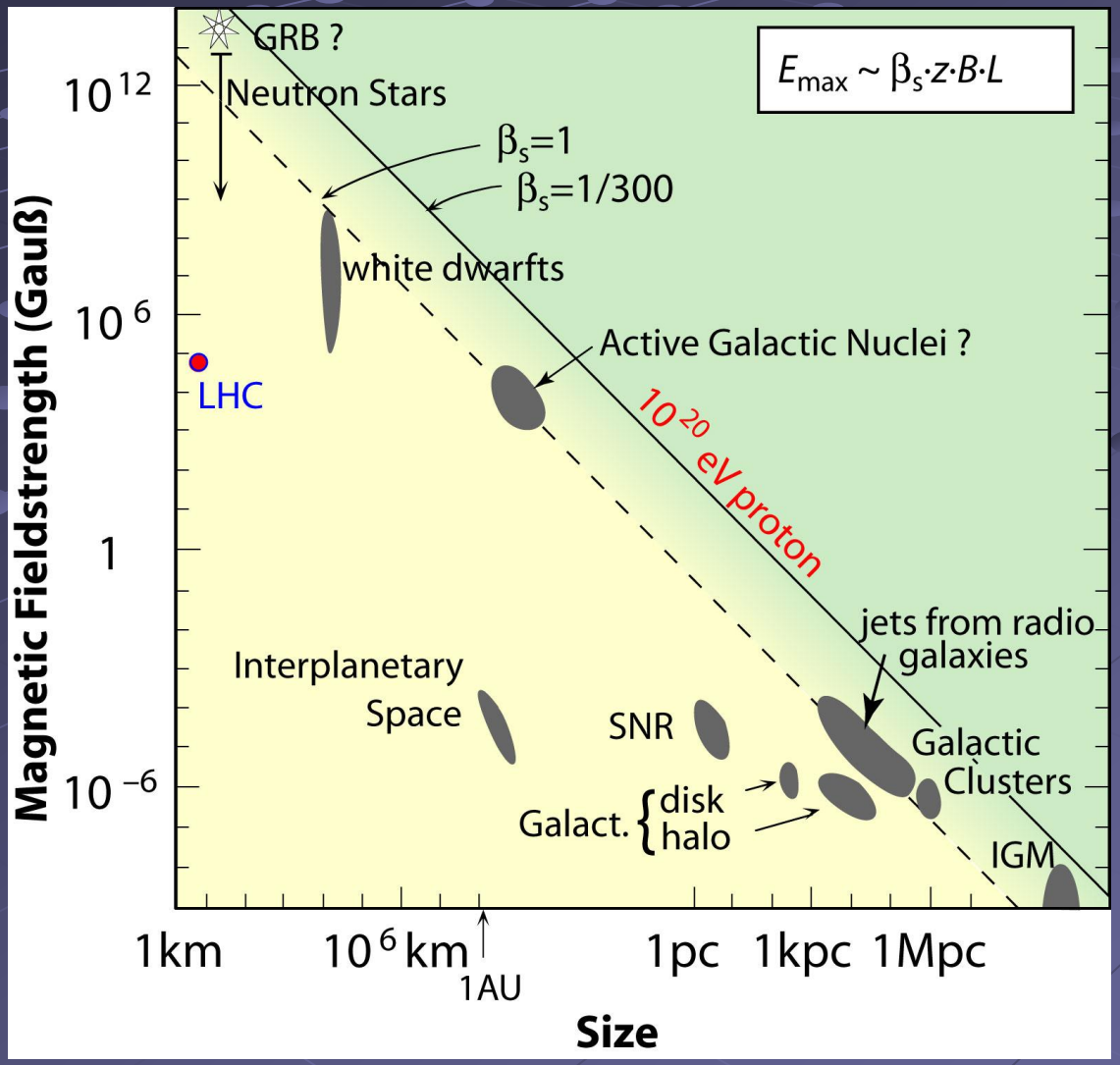
- Shock acceleration in extended objects or catastrophic events
- Acceleration in strong fields associated with accretion disks and compact rotating galaxies



Collision of galaxies NGC4038 and NGC4039 as seen by Hubble Space Telescope

LIMITS TO ACCELERATION

Hillas plot



No good candidates for ZeV accelerators in the known Universe!

POSSIBLE SOURCES

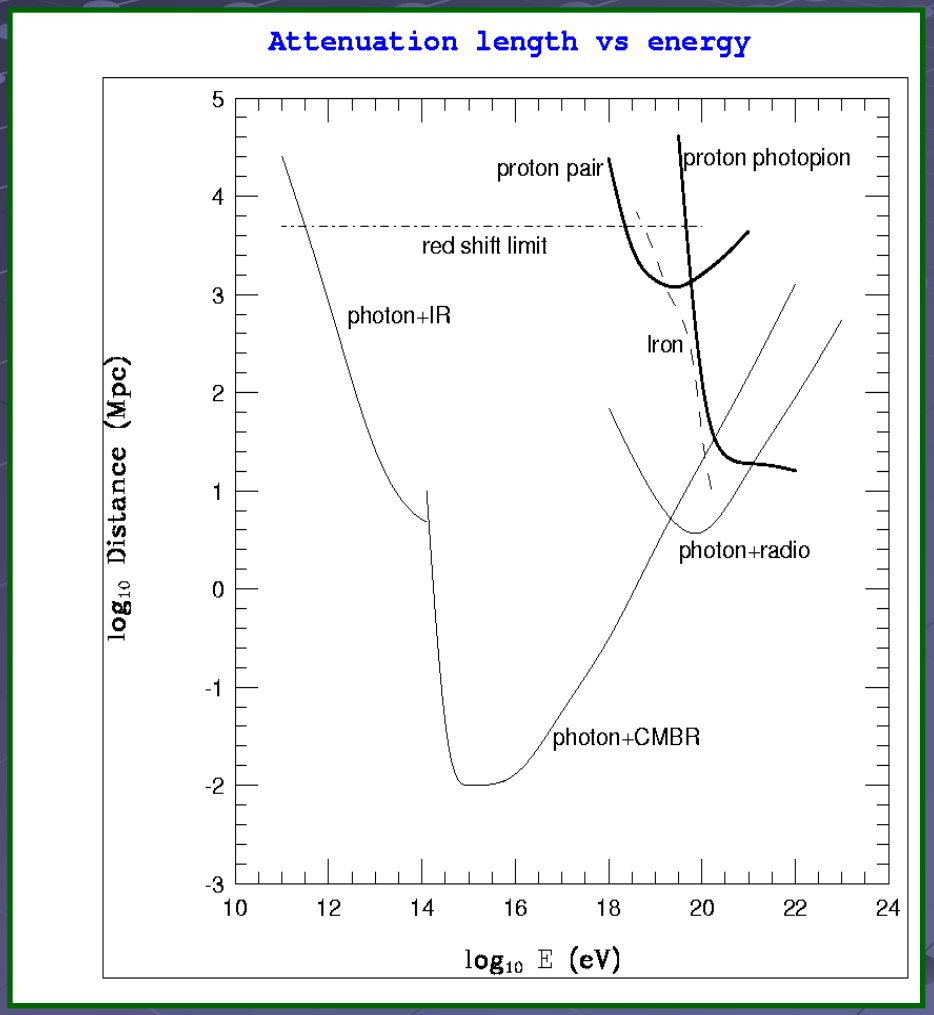
Top - Down Models

- Exotic Mechanisms
  - Decay of topological deffects
  - Relic monopoles
  - Etc.
- New Physics
  - Supersymmetric particles
  - Strongly interacting neutrinos
  - Decay of massive new long lived particles
  - Violation of LI
  - Etc.

Models do not reproduce the measured flux which is too high !

PROPAGATION

All known particles except neutrinos undergo interactions with Cosmic Microwave Background

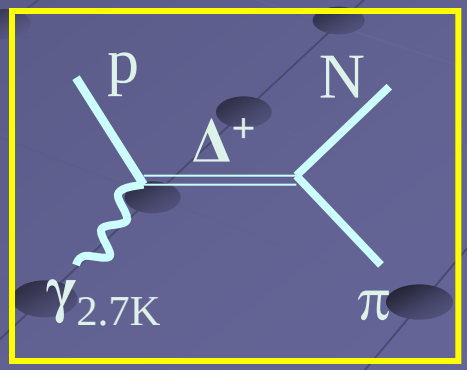


Example:

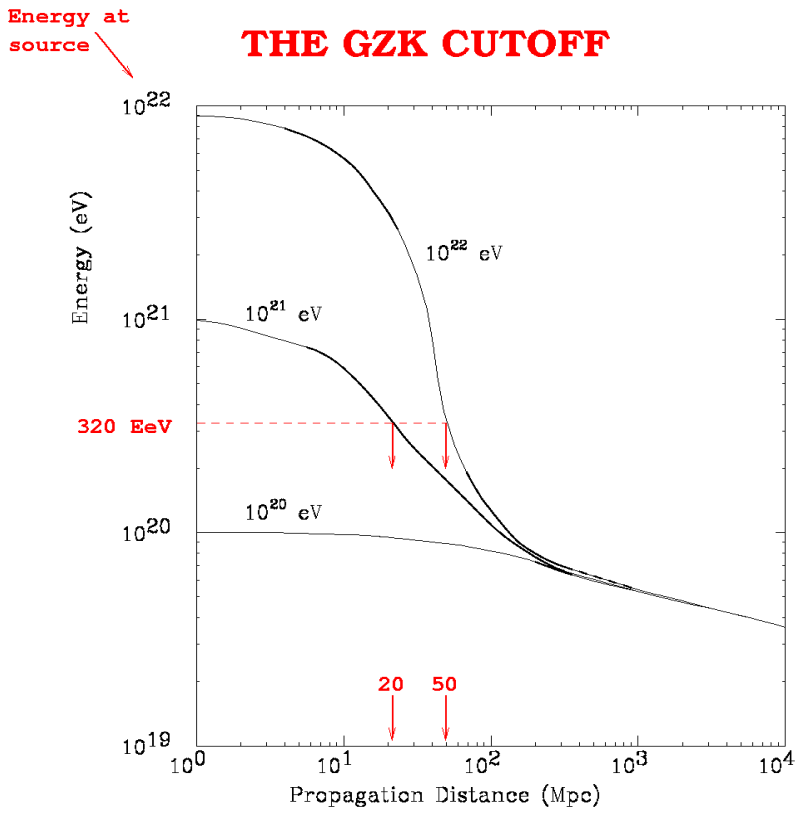
$p + \gamma_{2.7K} \rightarrow p + \pi^0$

$\rightarrow n + \pi^+$

For energy > 5 x 10^{19}



PROPAGATION



Energy attenuation of protons

Protons: photopion threshold @ ~50 EeV

Photons: pair production threshold @ ~200 TeV

Nuclei: photodisintegration above 50 EeV

Neutrinos: no problem!

For E>100 EeV, the source must be within ~50 Mpc

Greisen-Zatsepin-Kuzmin Cut-off

(Greisen '66, Zatsepin & Kuzmin '66)

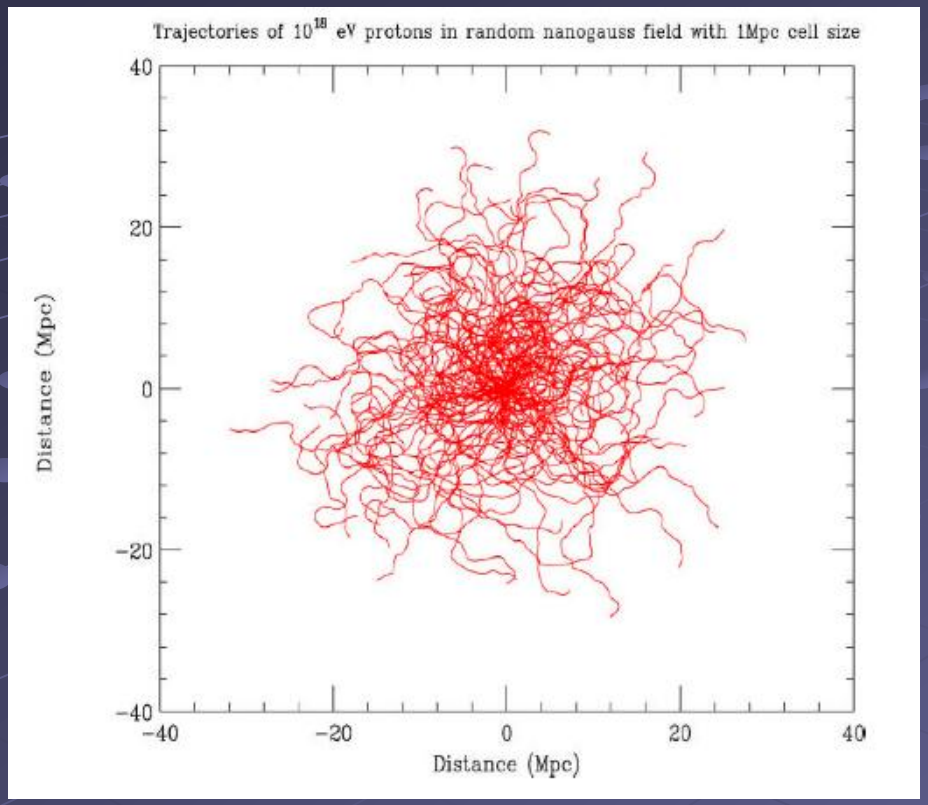
Particles > 5 x 10^{19} eV

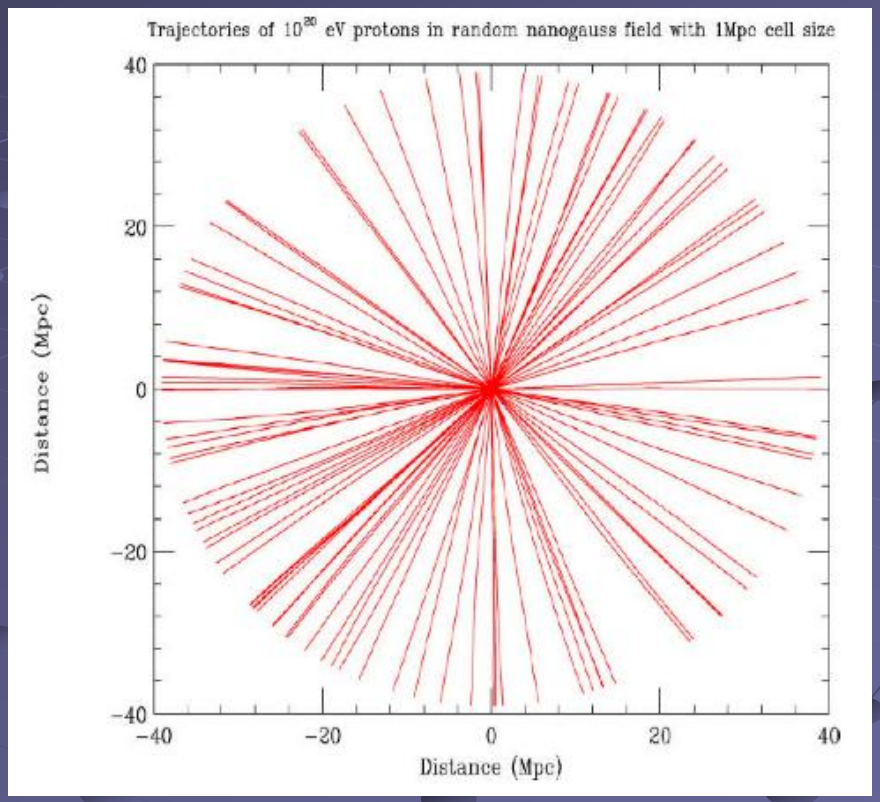
must be < 50 Mpc away

Size of the observable Universe

~ 4.000 MPc

MAGNETIC FIELD DEFLECTION



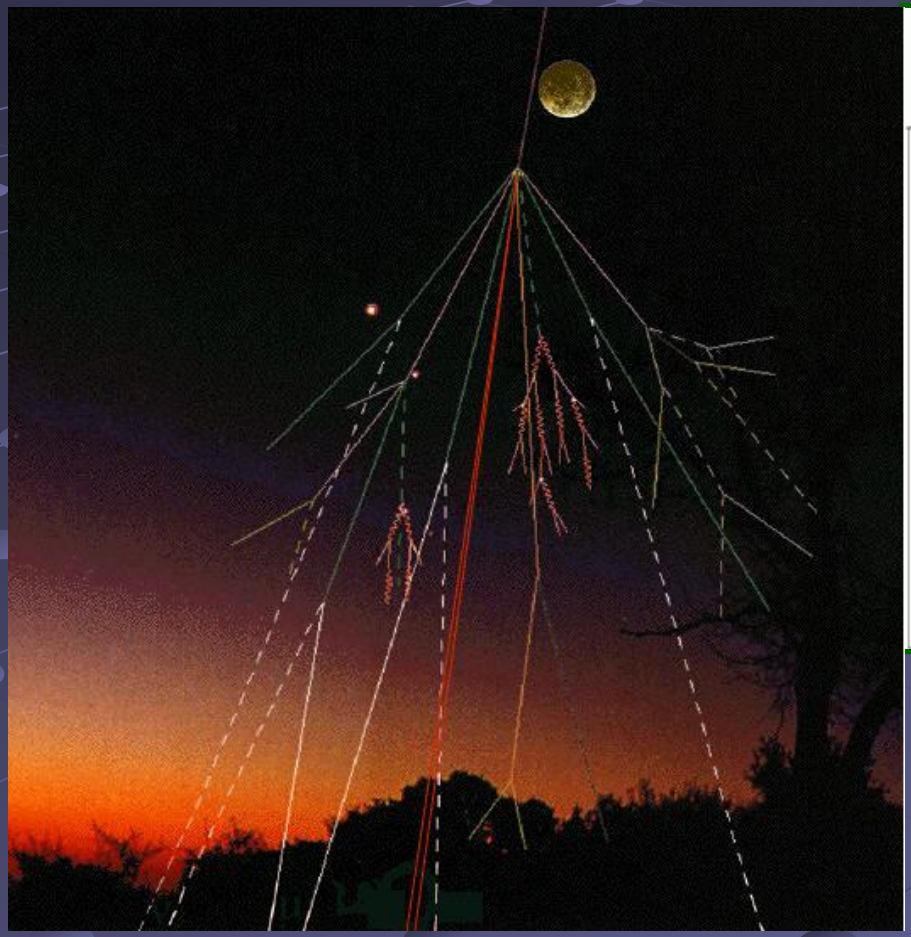


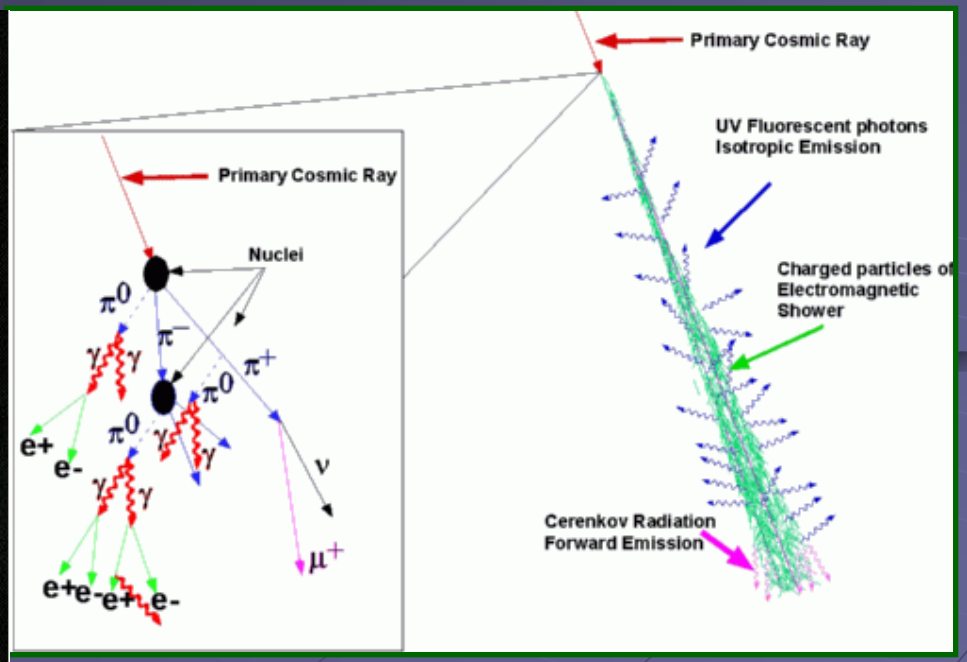
Above 100 EeV $\Delta\phi < 2^0$ - larger than experimental resolution!

A window to CR astronomy ?

EXPERIMENTAL TECHNIQUE

Measurement of extensive air showers





Calorimetry

- Calorimeter – atmosphere
- Read out
  - Fluorescence detectors
  - Particle detector array

EXPERIMENTS

PAST

- **Volcano Ranch, USA**
  - Scintillators
- **Haverah Park, UK**
  - Water Čerenkov
- **SUGAR, Australia**
  - Scintillators
- **Fly's Eye, USA**
  - Atmospheric Fluorescence
- **AGASA, Japan**
  - Scintillators, muon detectors
- **HiRes, USA**
  - Atmospheric Fluorescence

PRESENT

- **Yakutsk, Russia**
  - Scintillators, Atmospheric Čerenkov
- **P. Auger, Argentina**
  - Hybrid: Atmospheric Fluorescence, Water Čerenkov
- **Telescope Array**
  - Atmospheric Fluorescence, Scintillator Array

FUTURE

- **AirWatch: OWL – JEM/EUSO - TUS**
  - Atmospheric Fluorescence

PIERRE AUGER OBSERVATORY

A cosmic ray observatory designed for a high statistics study of

The Highest Energy Cosmic Rays (10^{19} - 10^{21} eV)

using

Two Large Air Shower Detectors

Mendoza, Argentina
(observatory fully operational)

Colorado, USA
(design and proposal in preparation)

P. AUGER COLLABORATION


Argentina


Australia


Bolivia


Brazil


Croatia


Czech Republic


France


Germany


Italy


Mexico


Netherlands


Poland


Portugal


Slovenia


Spain


UK

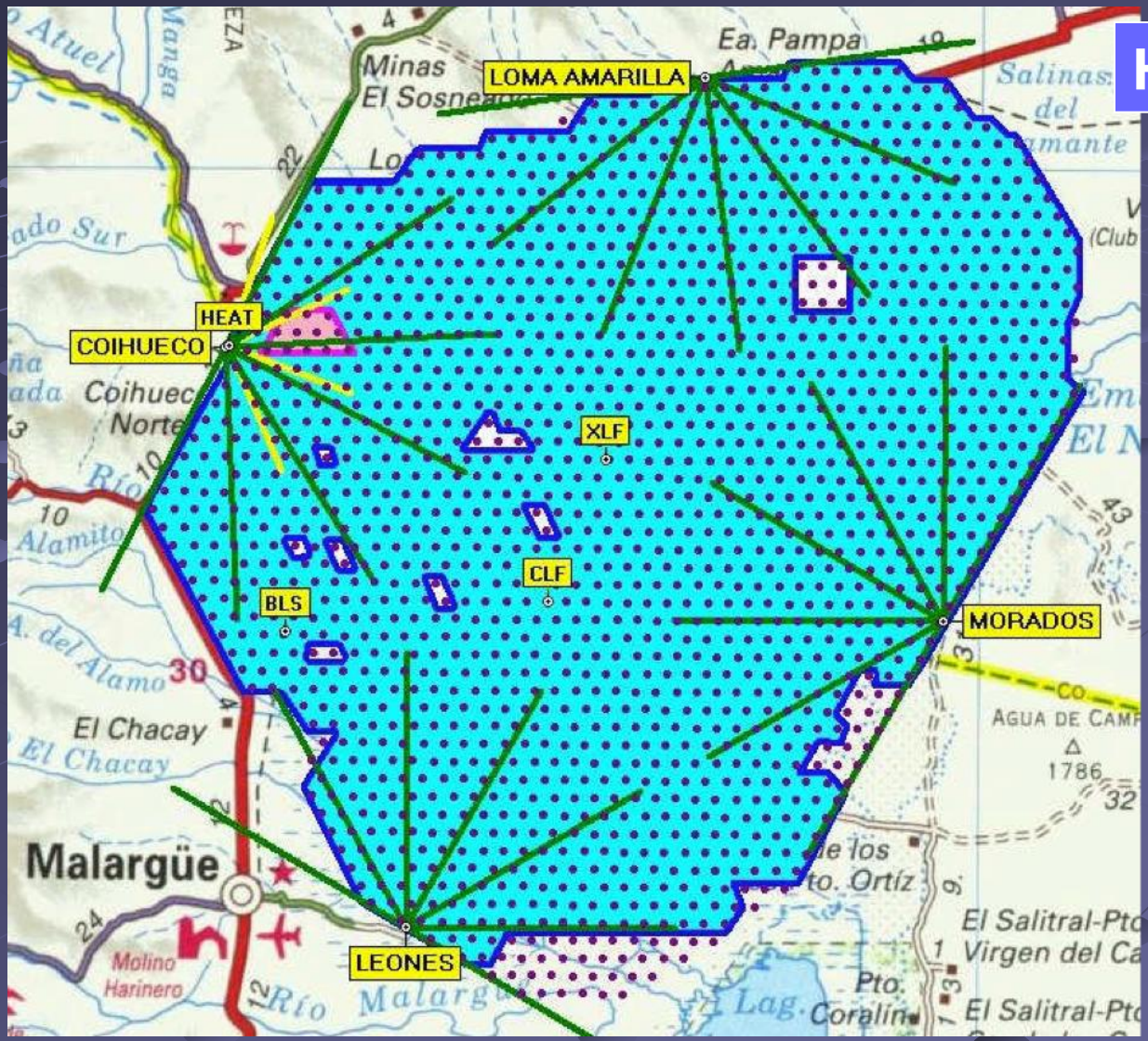

USA


Vietnam

~ 450 physicist from ~ 100 institutions

18 countries

SOUTHERN OBSERVATORY



HYBRID DETECTOR

SD

- ~ 1.600 surface detectors with 1.5 km spacing

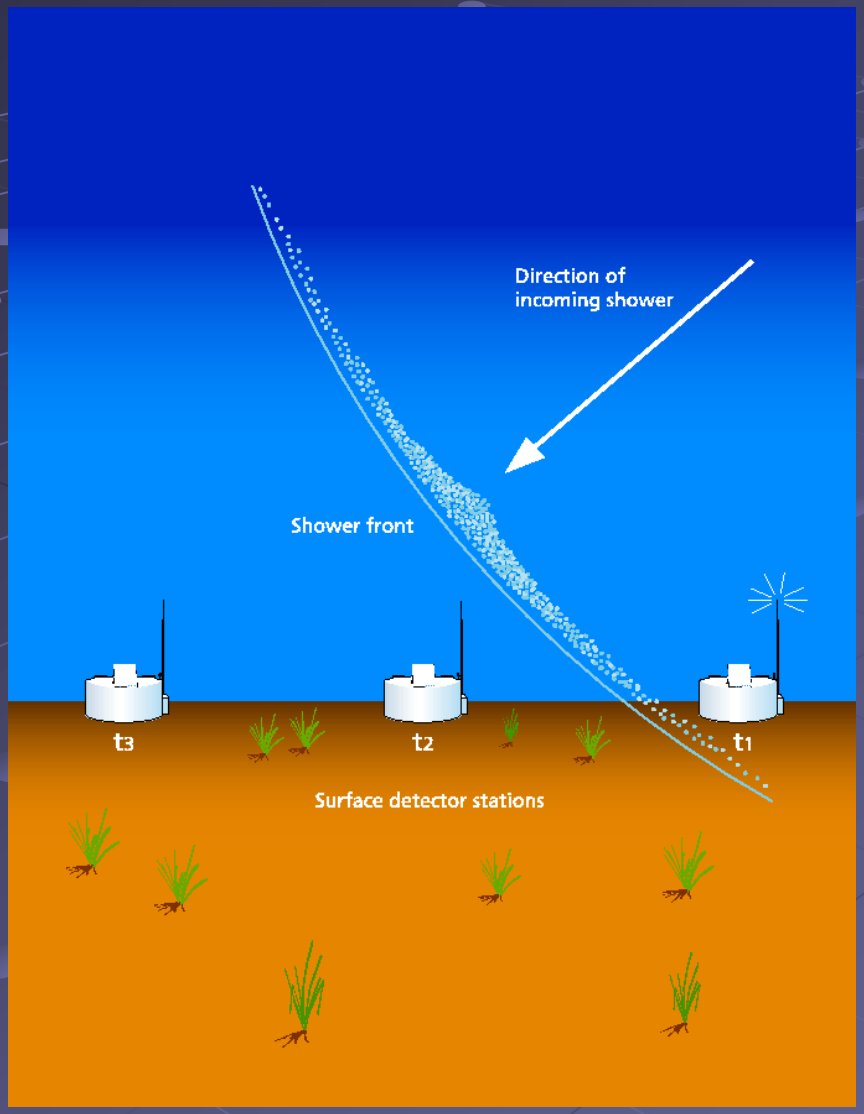
FD

- 4 fluorescence buildings with 6 telescopes each

World largest array

- 3.000 km^2 area
- 1 Auger year = 30 AGASA years (SD)

SURFACE DETECTOR ARRAY

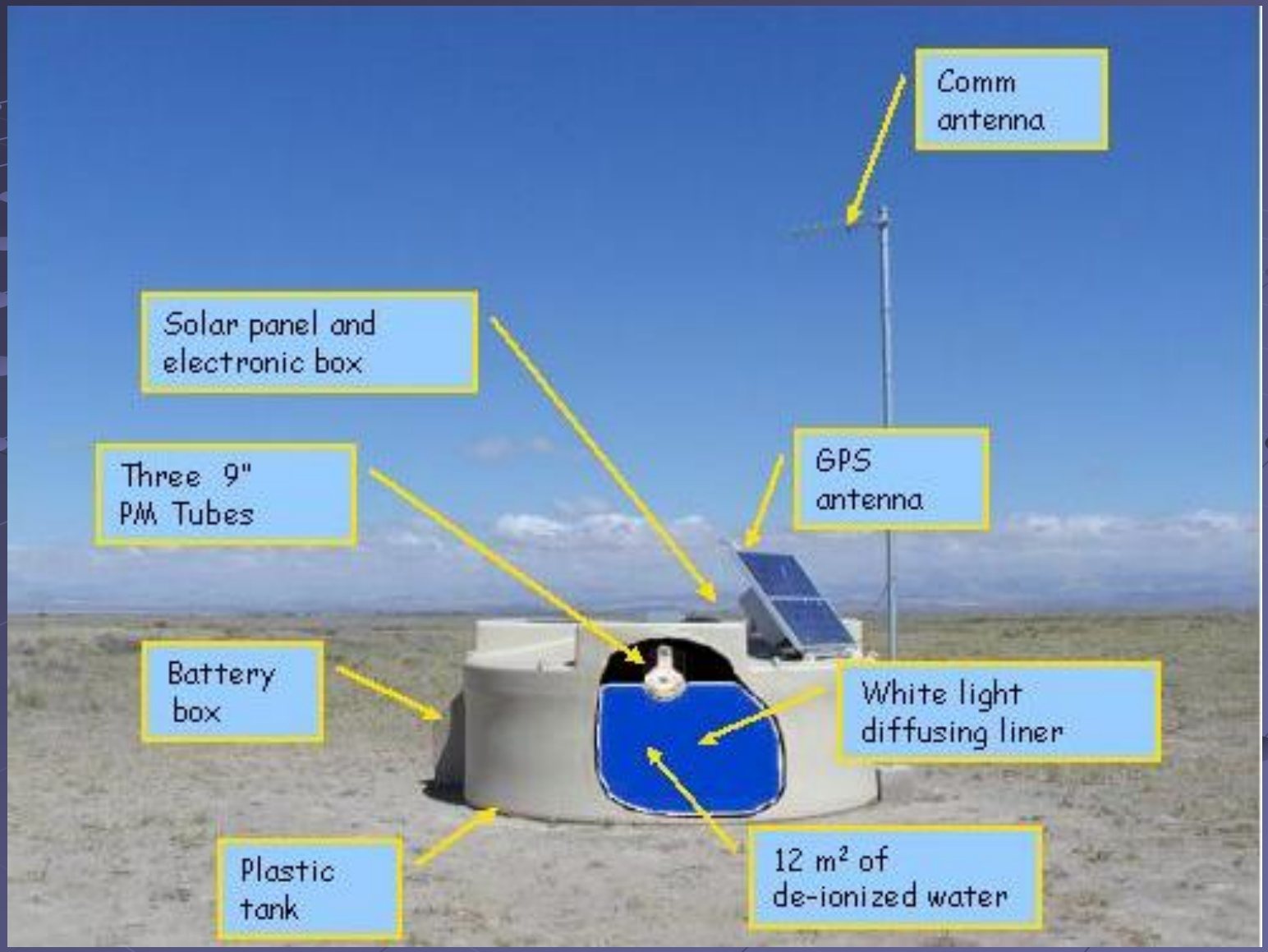


Event timing and direction determination

- **Shower timing** → **Shower angle**
- **Particle density** → **Shower energy**
- **Muon number**
- **Pulse rise time**

→ **Measure of primary mass**

WATER ČERENKOV DETECTOR

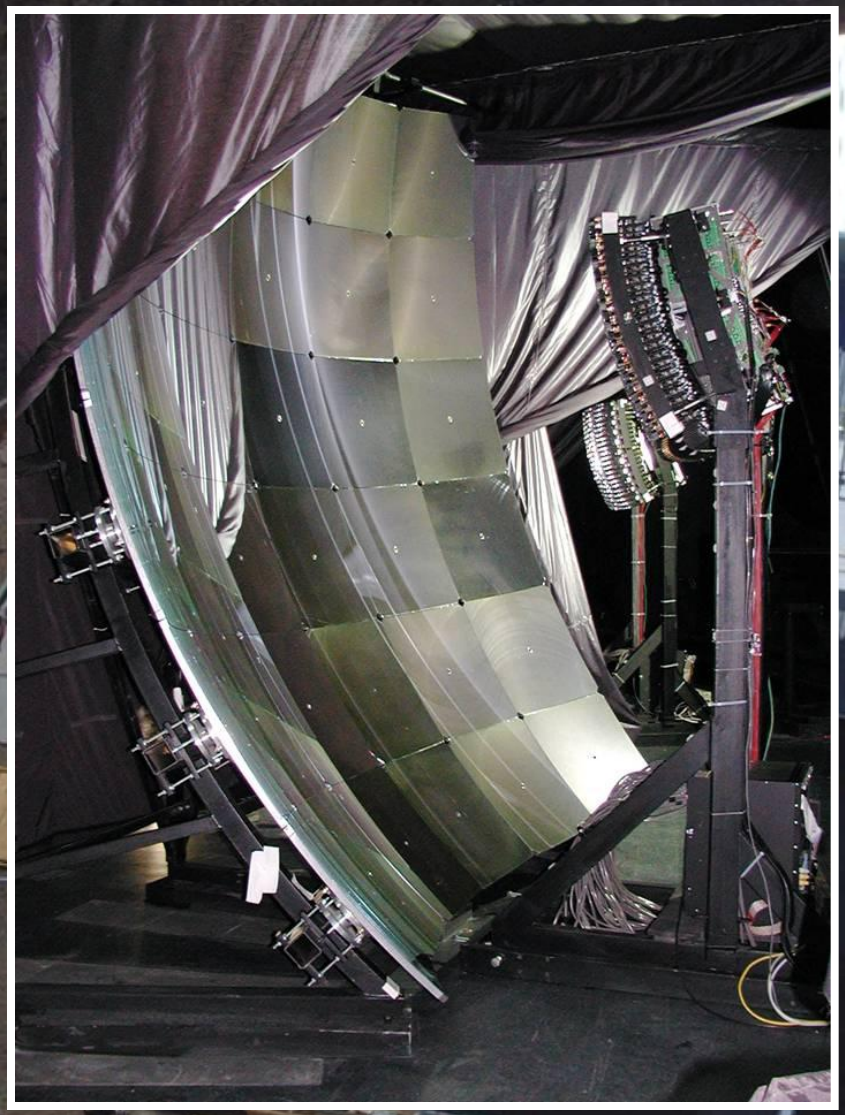


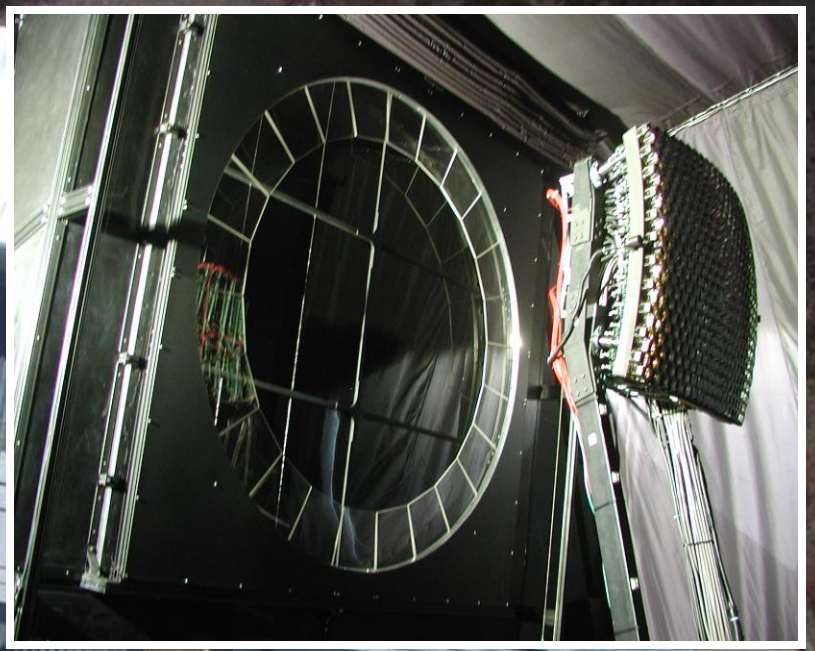
FLUORESCENCE DETECTOR

- **Shower ~ 90% electromagnetic**
- **Ionization of nitrogen measured directly**

- **Calorimetric energy measurement**
- **Measure of shower development**

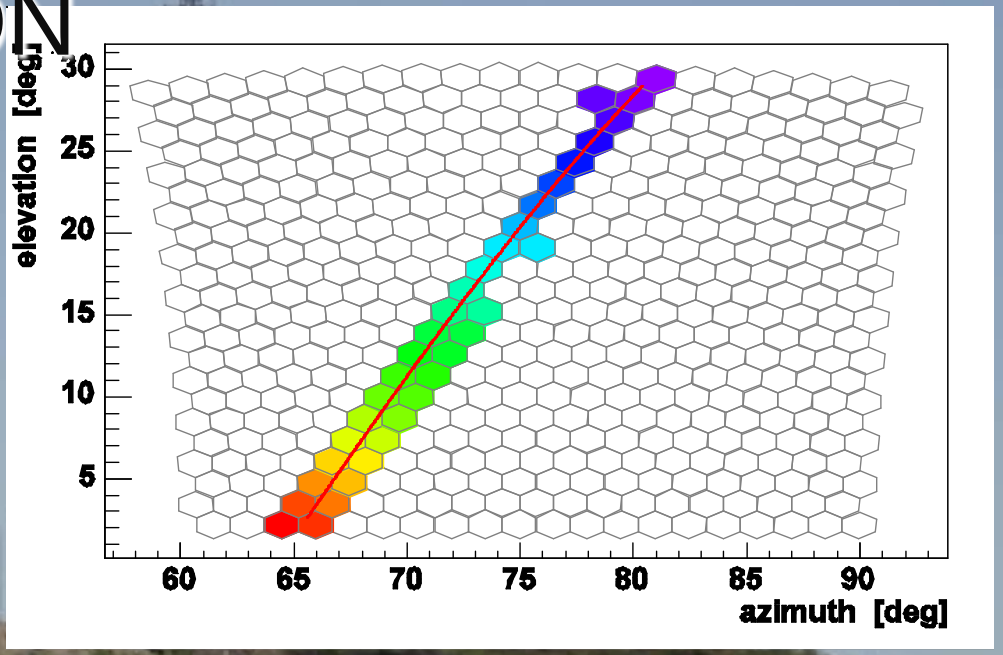
FLUORESCENCE DETECTOR

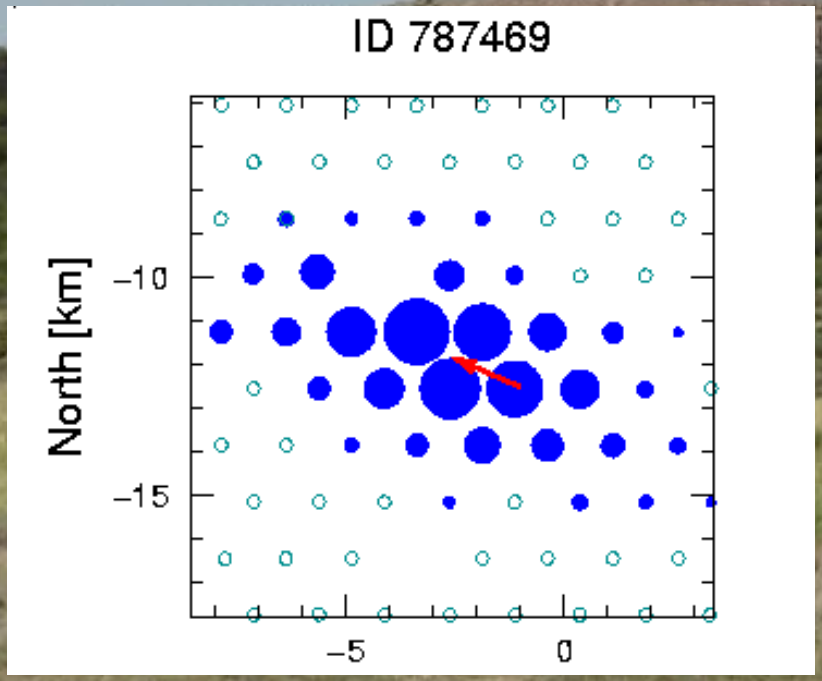




Fluorescence telescopes:
***Number of telescopes:* 24**
***Mirrors:* 3.6 m x 3.6 m with field of view 30º x 30º, each telescope is equipped with 440 photomultipliers.**

HYBRID OPERATION





SPECTRUM

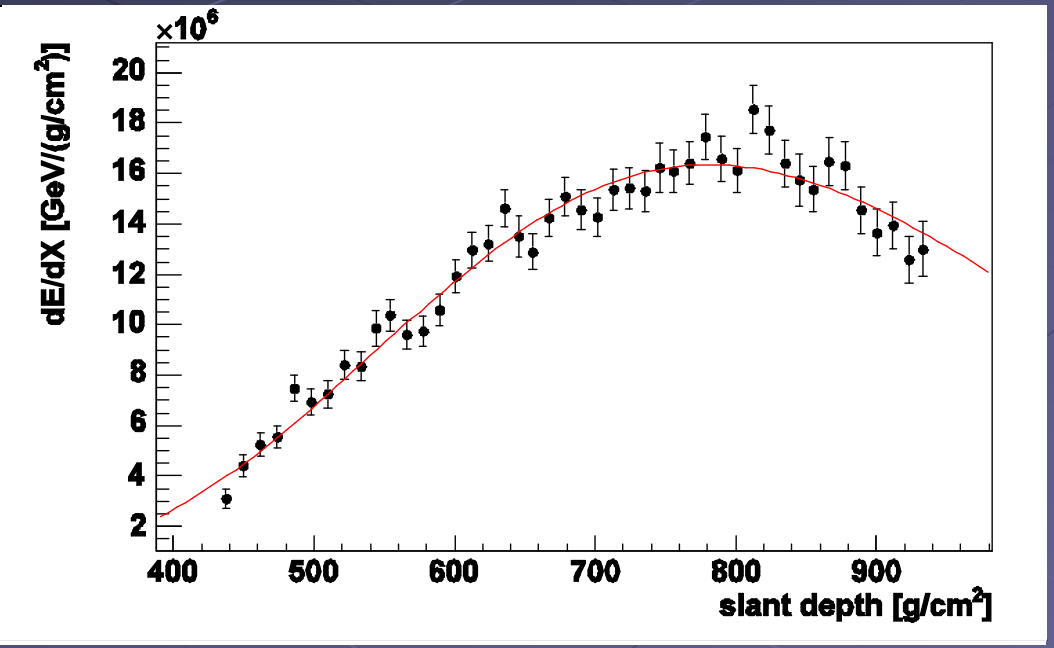
ENERGY MEASUREMENT

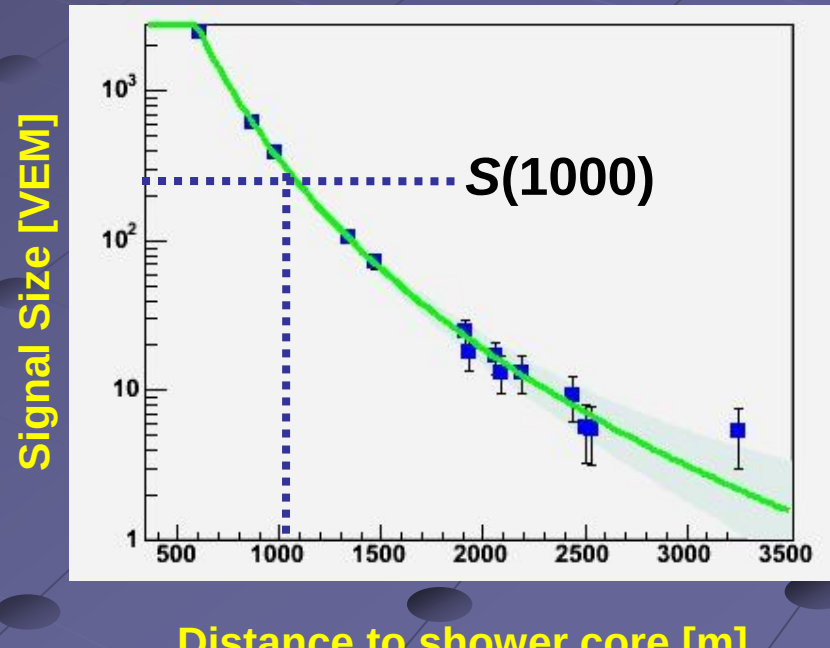
Fluorescence detector

- Measure light intensity along the track and integrate.
- Nearly calorimetric, model and mass independent.

Surface detector array

- Particle density S at fixed distance to the shower core is related to the shower energy via simulations.



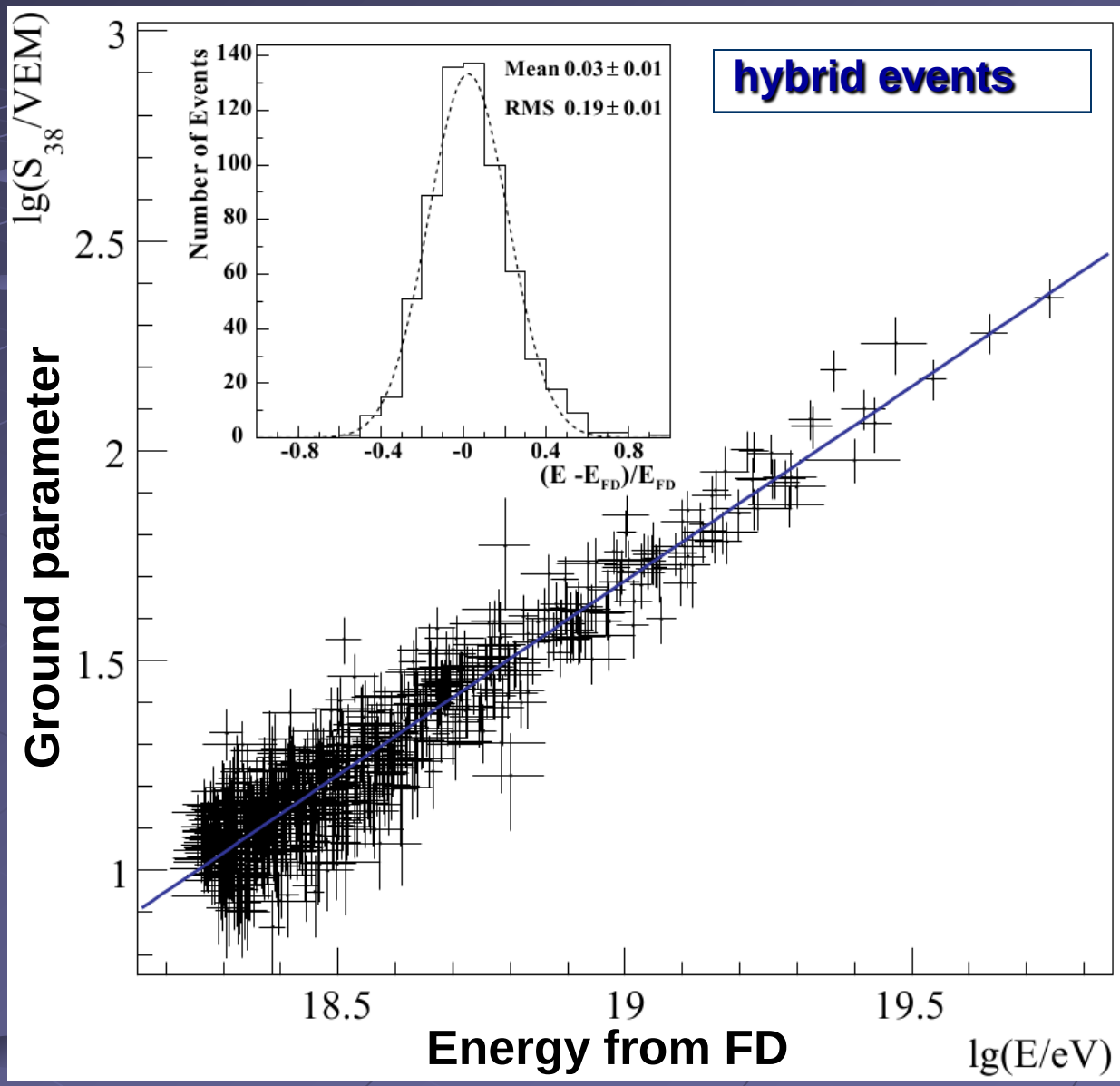


ENERGY DETERMINATION

Energy scale is determined from data

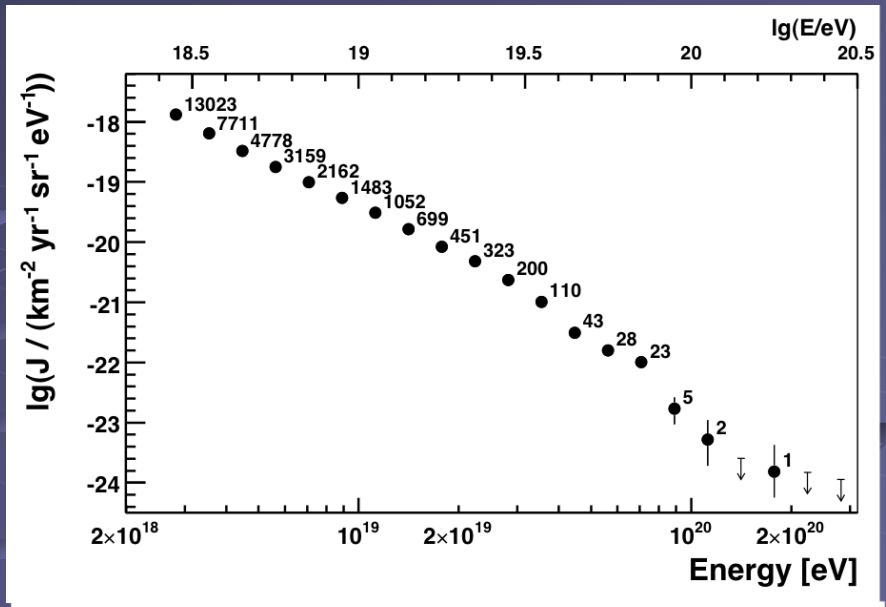
- Aperture is determined by geometry of surface detector array.
- Hybrid data is used to establsh conection between S(1000) and shower energy as measured by FD
- Correction for elevation angle relies on measured data only (CIC).

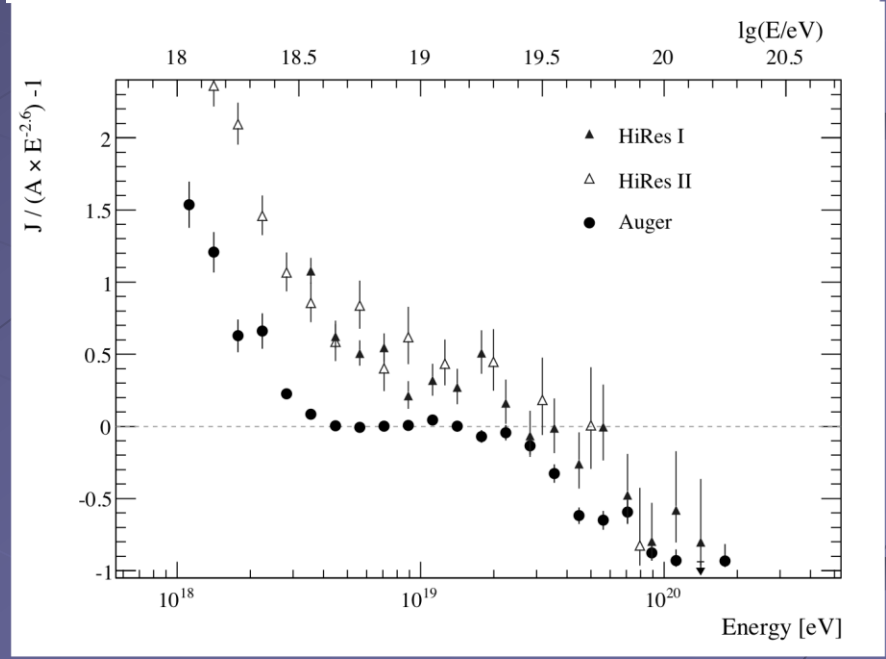
Energy scale is free of simulations.



ENERGY SPECTRUM (< 60^0)

- Spectral index changes from 2.69 ± 0.02 ± 0.06 to 4.2 ± 0.4 ± 0.1.
- Comparison of spectrum to unbroken power law (TP test): 6 σ.
- Confirms observation of similar suppression in HiRes data.
- Consistent with longstanding prediction by Greisen and Zatsepin-Kuzmin (GZK) that cosmic ray flux is attenuated above ~ 6×10^{19} eV due to interaction with CMB
- Implications if GZK: cosmic rays above ~ 6×10^{19} eV originate within 100 Mpc.





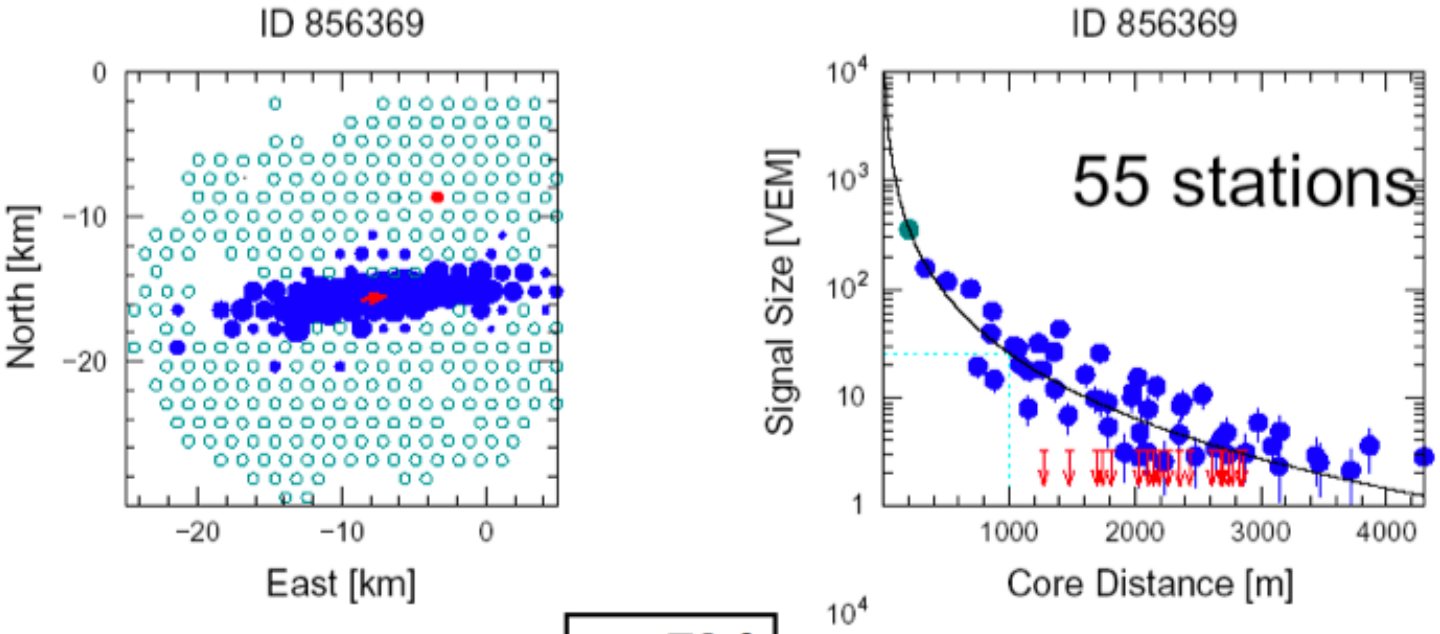
SYSTEMATIC ERRORS

Systematic uncertainties in the air fluorescence yield currently dominate but efforts to reduce this error are underway.

Source	Systematic uncertainty
Fluorescence yield	14%
P,T and humidity effects on yield	7%
Calibration	9.5%
Atmosphere	4%
Reconstruction	10%
Invisible energy	4%
TOTAL	22%

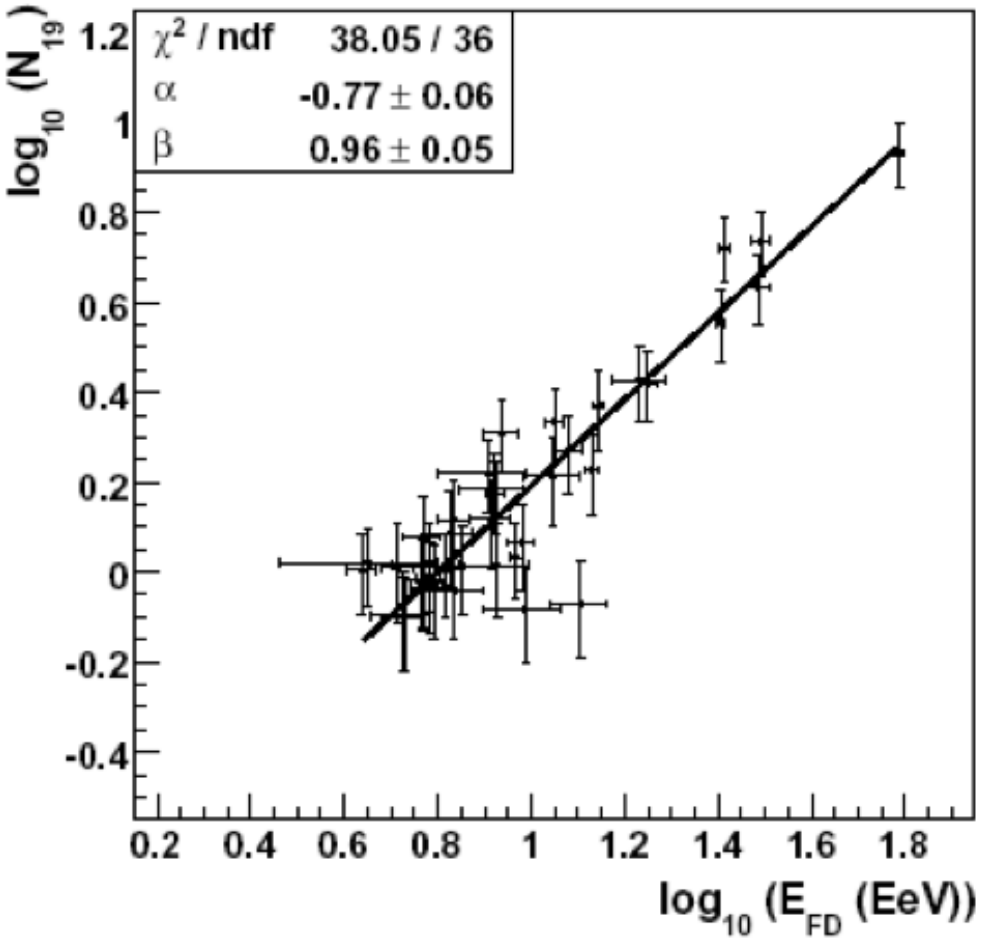
INCLINED EVENT

Inclined Events offer additional aperture



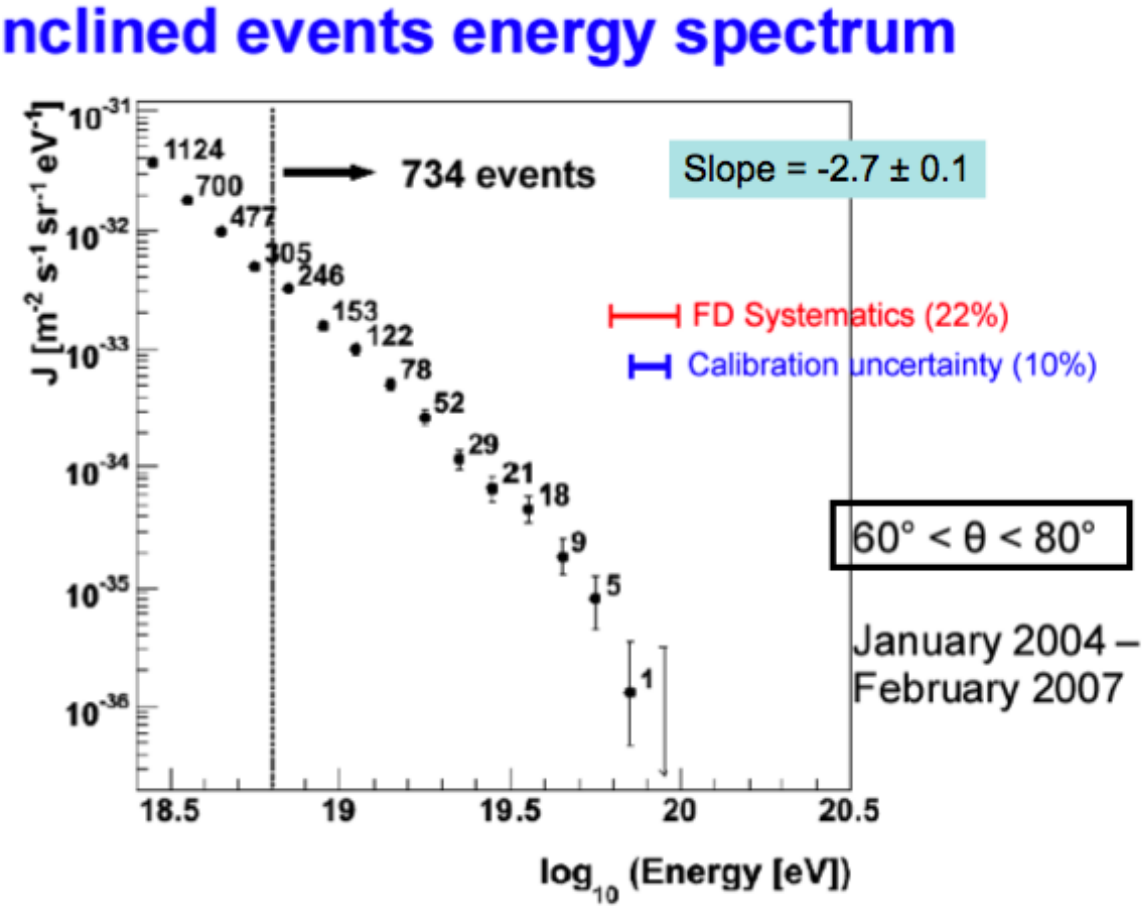
θ = 79 °

INCLINED SHOWERS



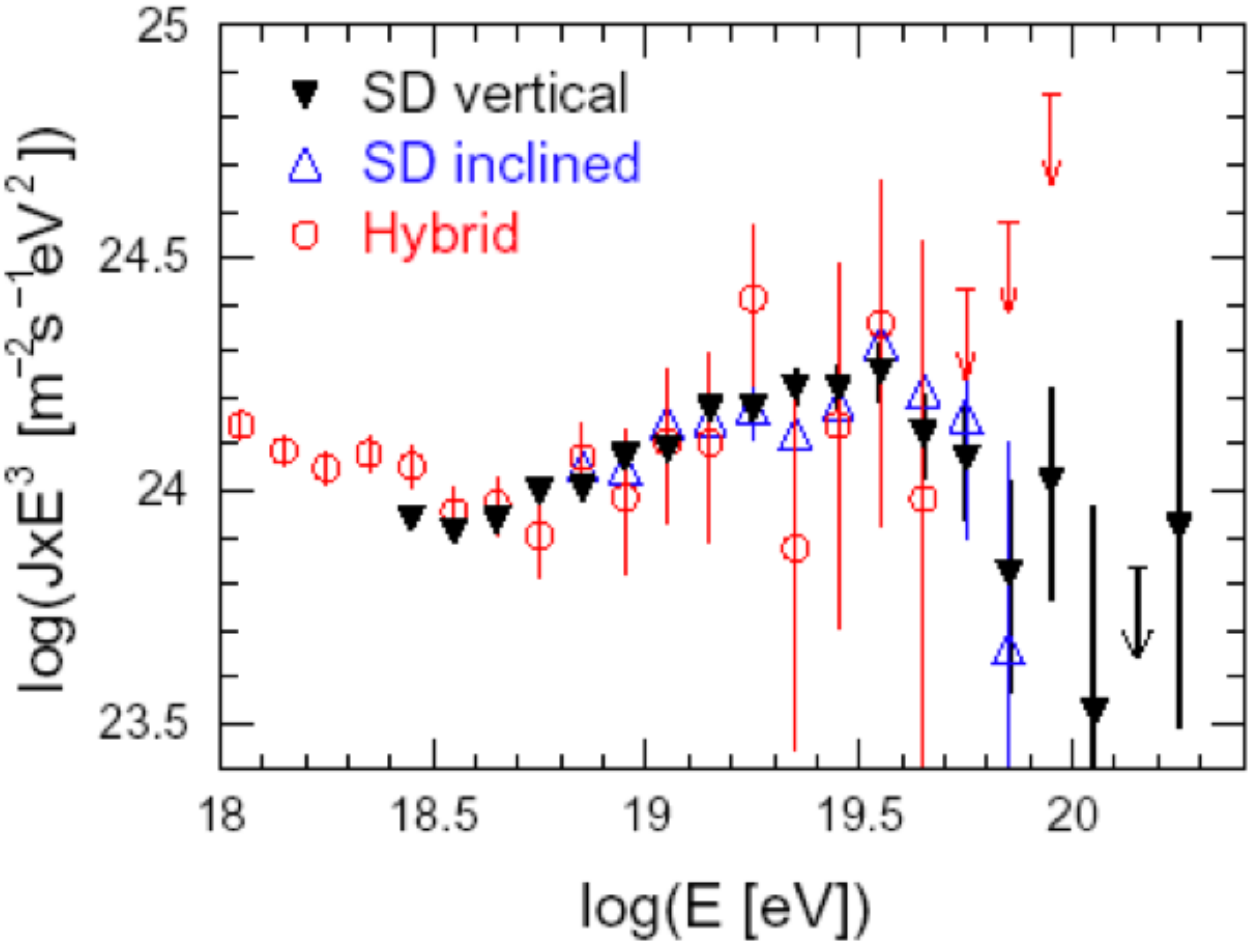
Calibration curve for inclined showers

SPECTRUM - INCLINED EVENTS



Exposure 1510 km^2 yr sr (29% of θ<60°)

SPECTRUM COMPARISON



CHEMICAL COMPOSITION

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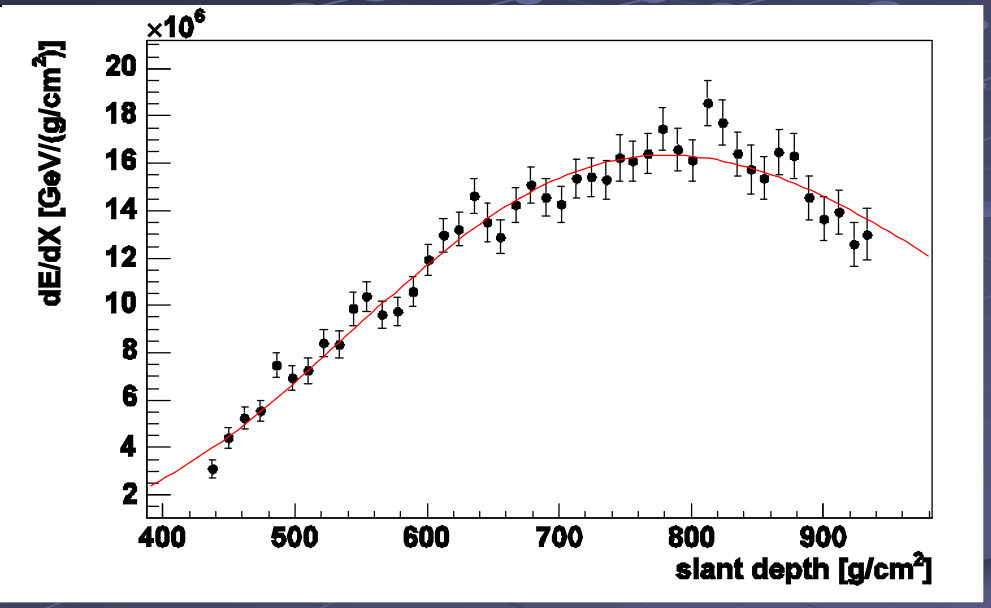
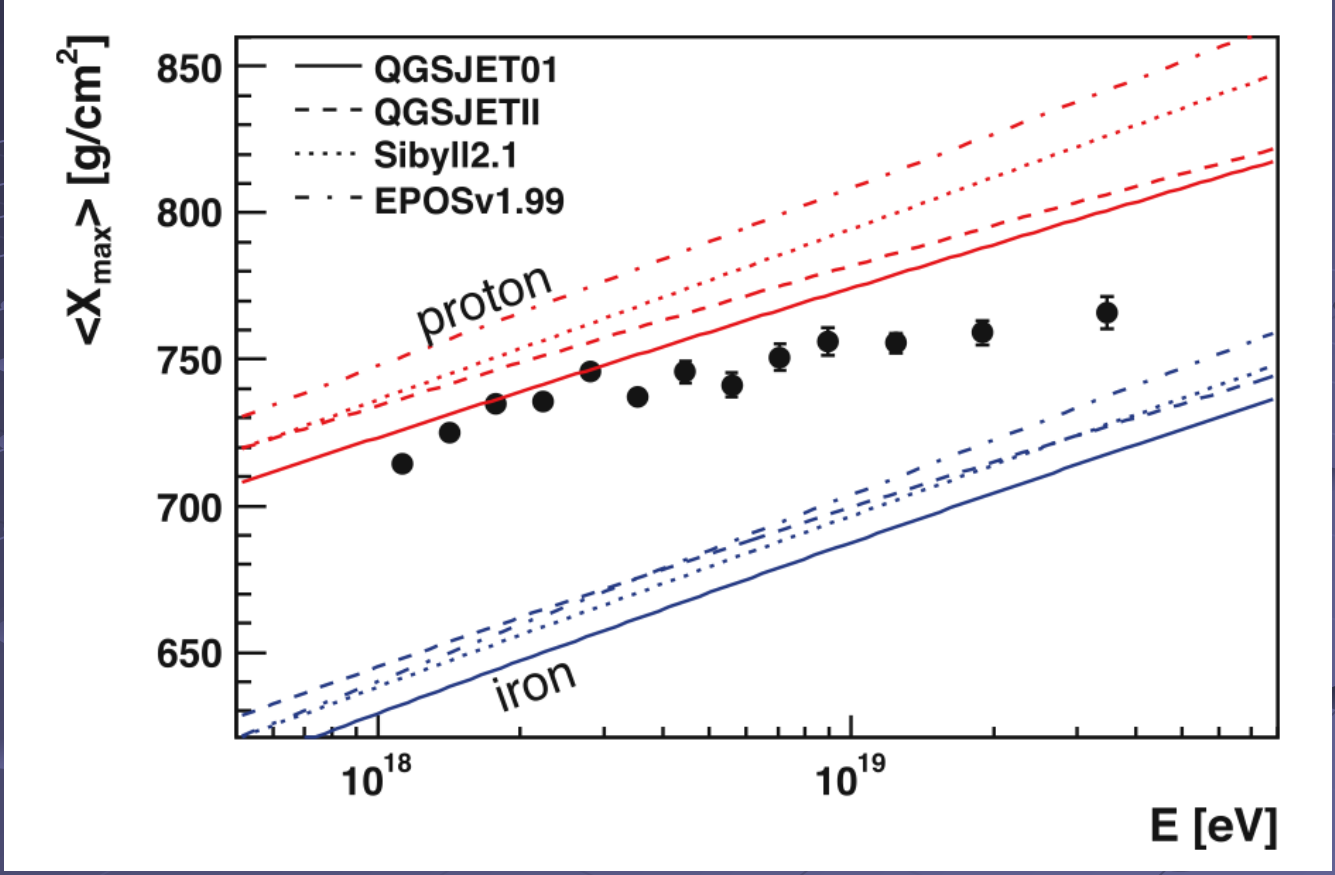


- Speed of air shower development depends on the mass of the primary: a heavier nucleus induces earlier shower development.
- FDs measure the height of the shower maximum directly, but intrinsic fluctuations in the depth of shower maximum are large, so an identification of the primary on an event-by-event basis is not possible.

- Study mean height of shower maximum for a large data sample.
- Elongation rate (mean shower maximum vs. energy) indicates the dominant chemical component, but we have to compare to simulations to interpret the data (strong model dependence!).

CHEMICAL COMPOSITION

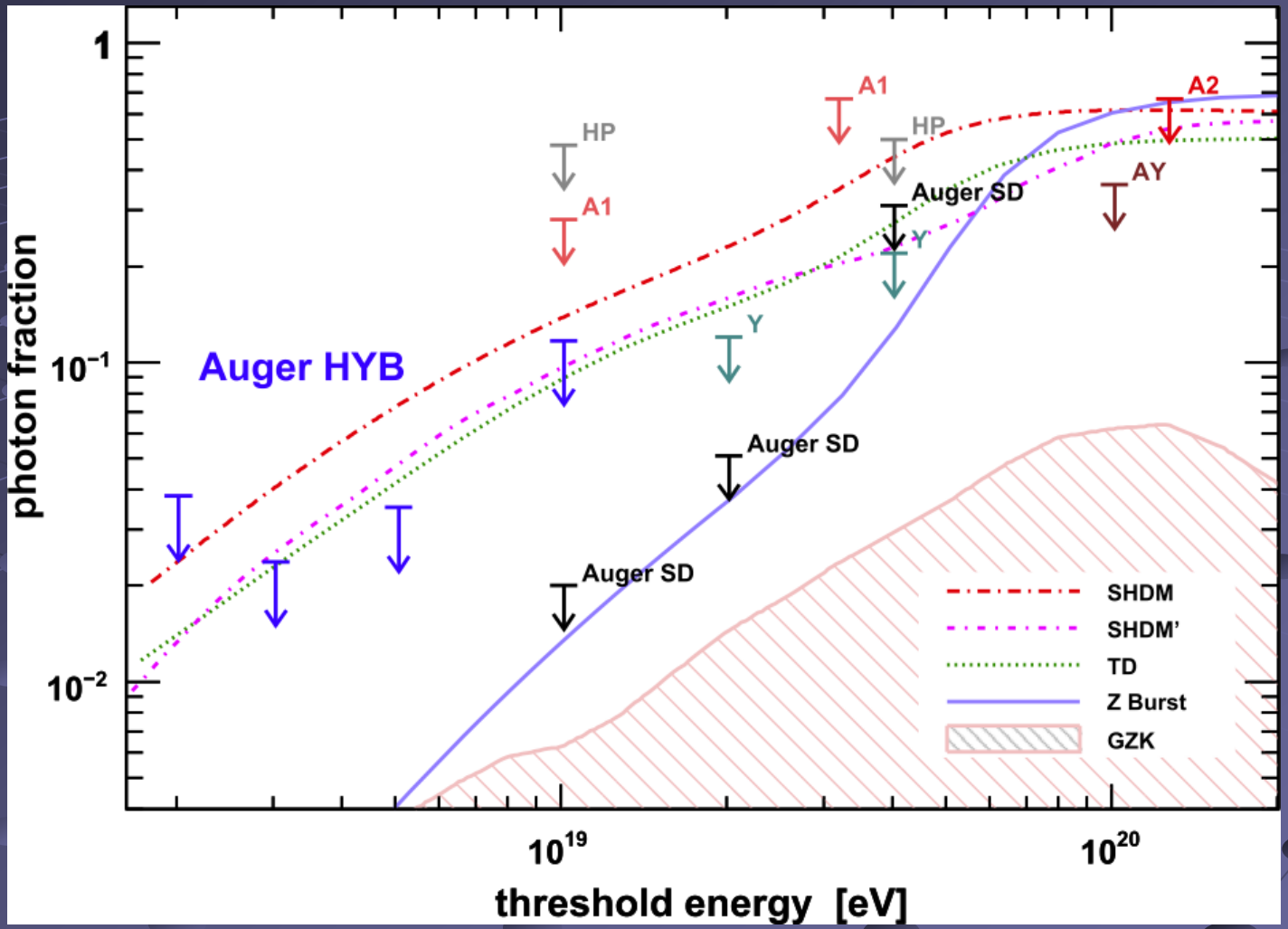


- Proton primaries determined by patterns in sky distribution – new interactions to explain composition measurements
- Heavy primaries determined by patterns in sky distribution – new source models to explain heavy dominance.

Too early for conclusions!

PHOTON FLUX

PHOTON FLUX



TOP – DOWN MODELS DISFAVORED !

ARRIVAL DIRECTIONS

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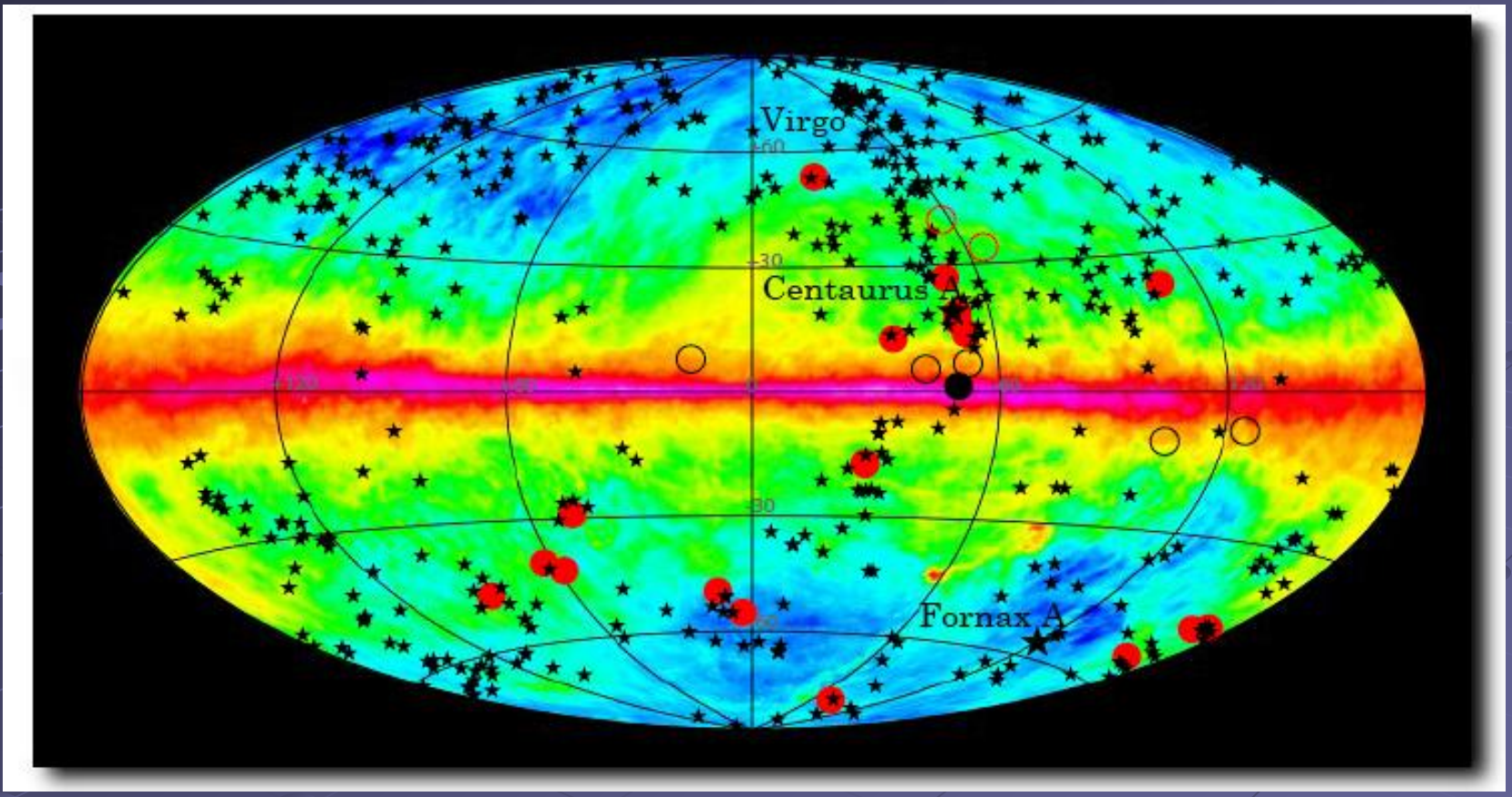


- The V-C catalog is likely to be incomplete near the Galactic plane also the Galactic magnetic field is stronger in the disk. Out of the 7 events out of the correlation, 5 are within 12º of the Galactic Plane.
- Cutting on the Galactic Plane (|b|<12º) the minimum reads :

  $P = 2 \times 10^{-10}$ at E=57 EeV, z=0.017 and ψ =3.2º,

  with 19 of of 21 events in correlation where 5 are expected

Short article published in Science 318 (2007) 938-943.

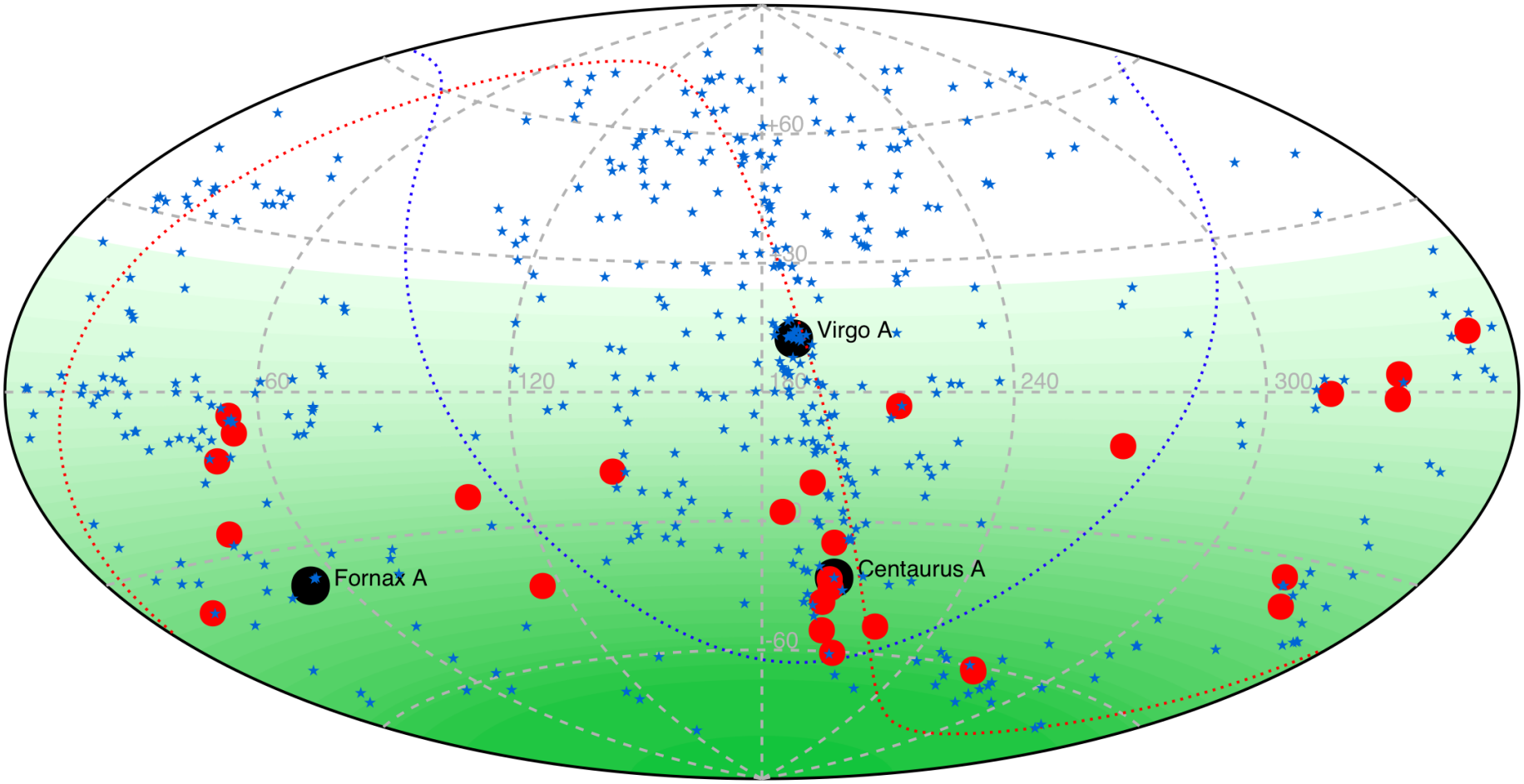
Long article published in Astroparticle physic 29 (2008) 188.

ARRIVAL DIRECTIONS

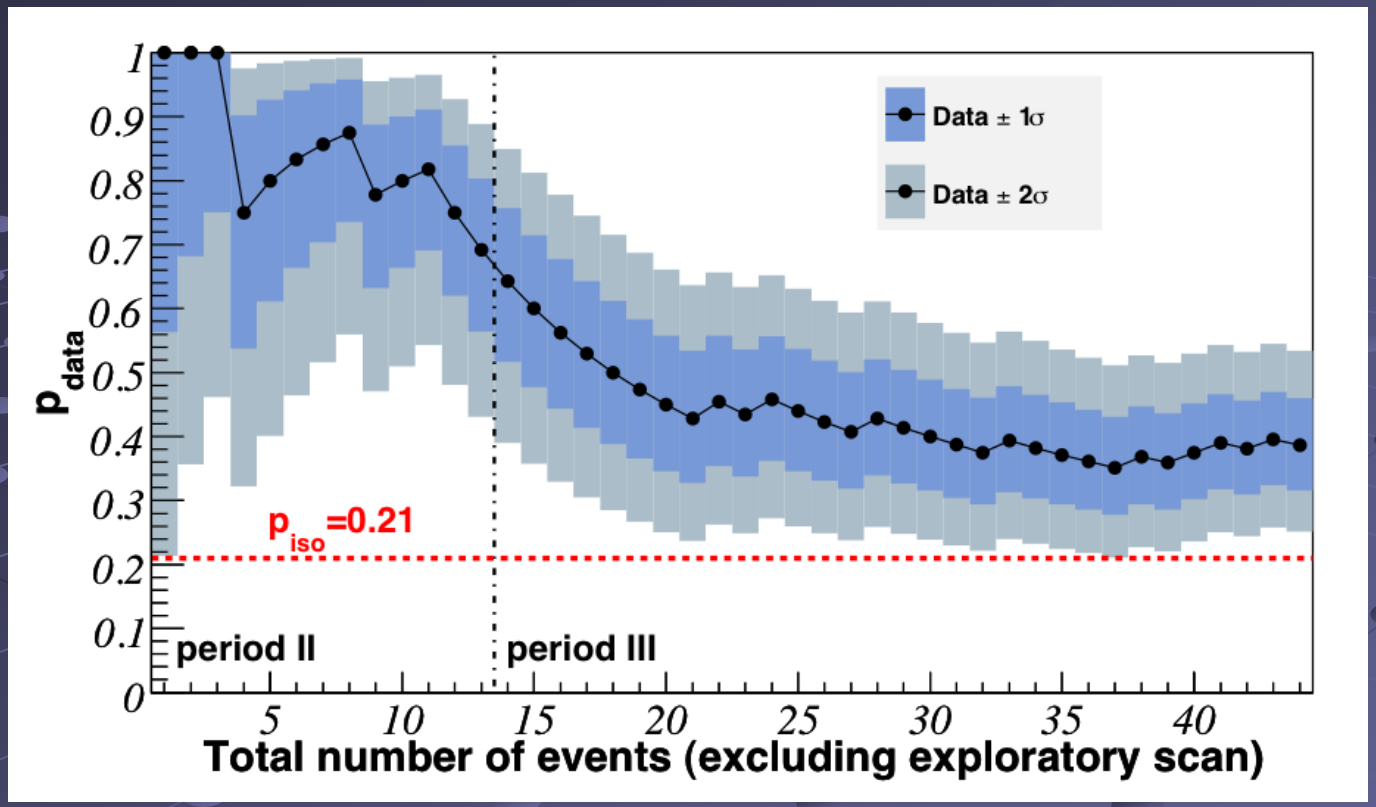
Acceleration sites

- Can we say something about the sources?
  - They are not in the Milky Way
  - They are likely astrophysical
  - AGN are plausible acceleration sites
- More data are needed to identify the sources and their characteristics

CORRELATIONS WITH AGNs



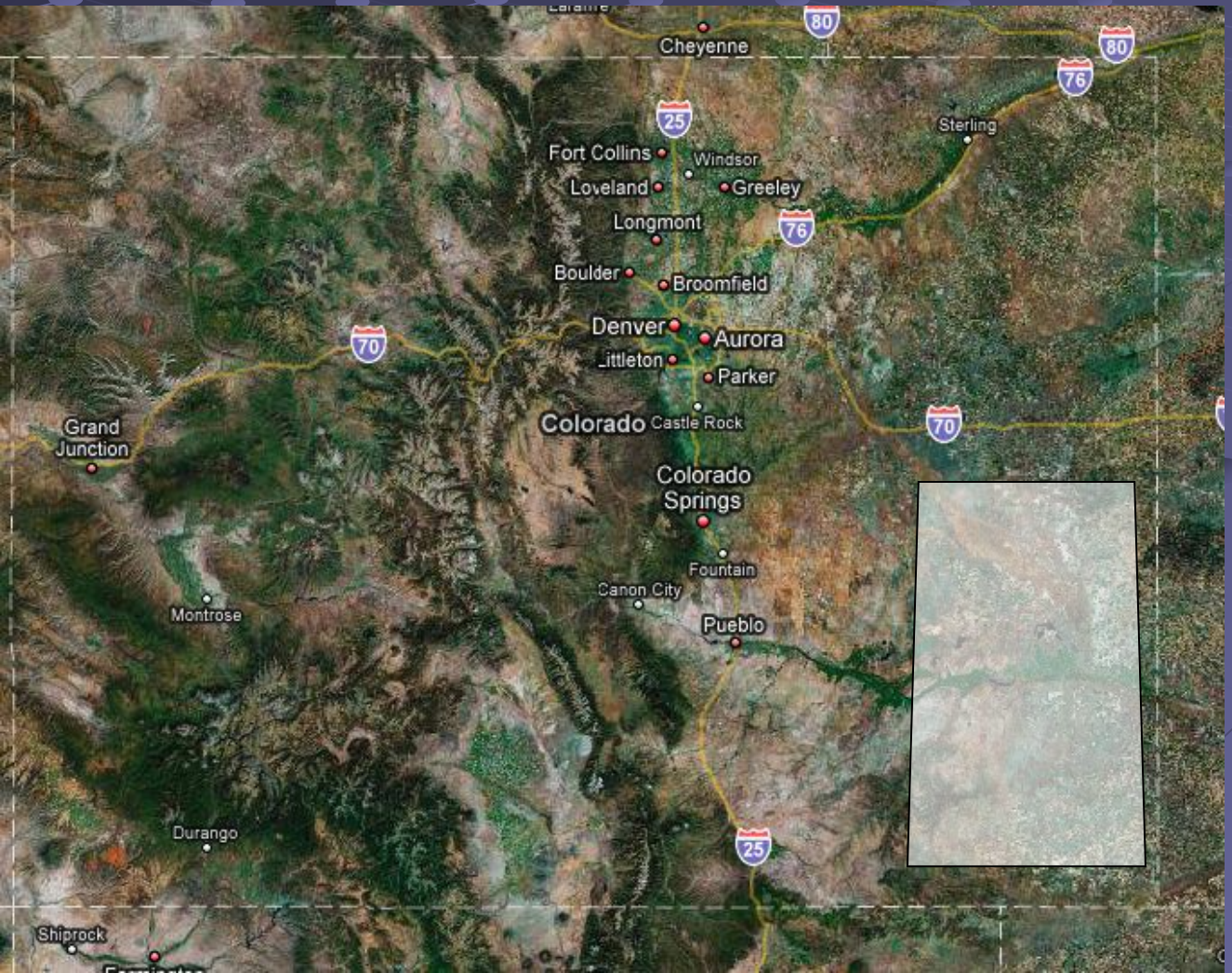
CORRELATIONS WITH AGNs



- Signal strength for AGN correlations is not as strong as the first data suggested.
- Probability p_{signal} of correlating with an AGN appears to settle on a value around 0.4 - the null hypothesis corresponds to $p_0 = 0.21$
- Results still shows good correlation with matter.
- Several events close to Centaurus A.

FUTURE

- Much more statistics needed.
- Full sky coverage.



AUGER NORTH

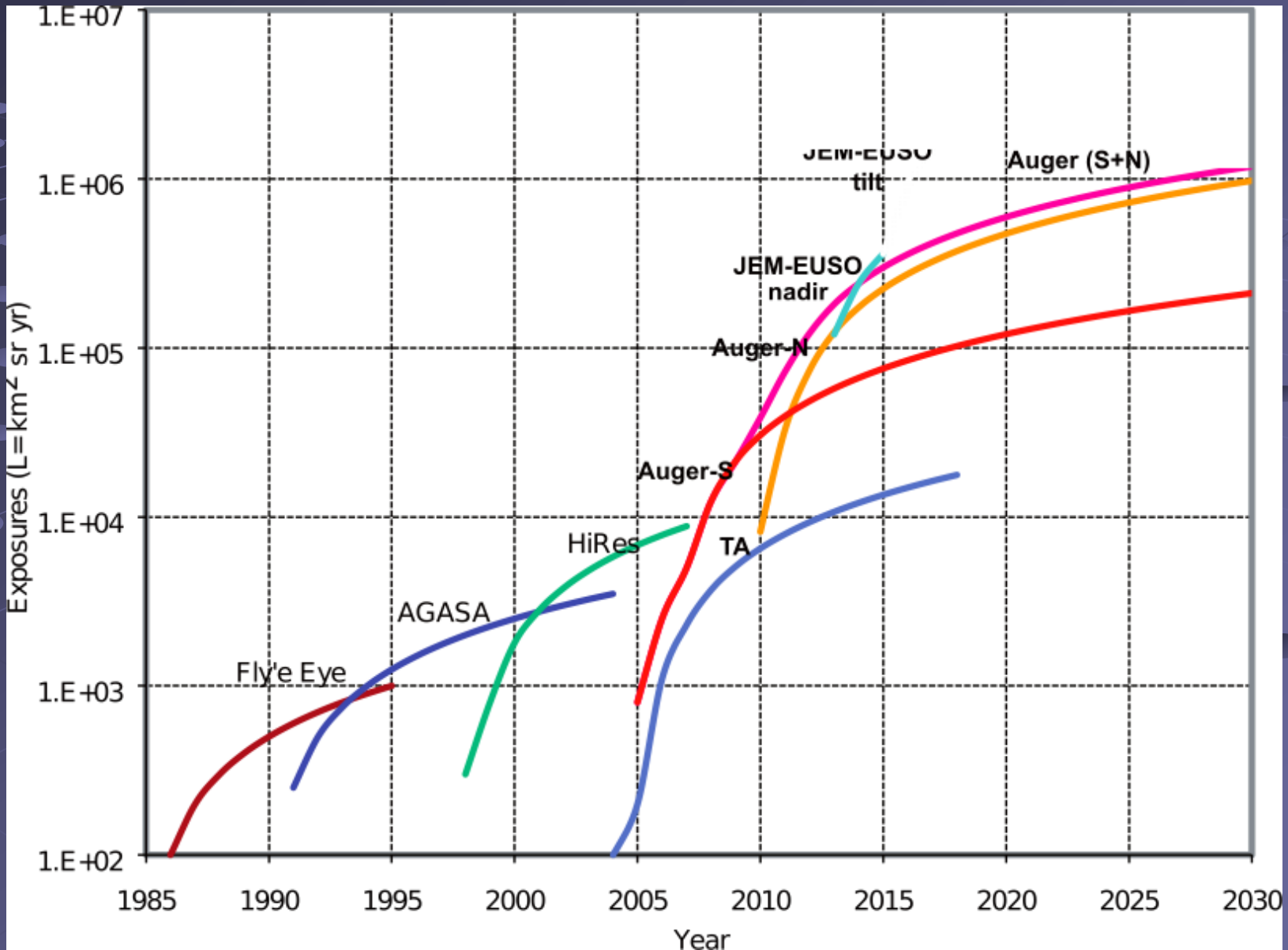
~ 20.000 km^2

Design report finished

AUGER NORTH

SIZE OF SLOVENIA

FUTURE - EXPOSURE



CONCLUSIONS

Pierre Auger Observatory

- Exposure is now 17,000 km^2 sr yr.
- Current SD statistics: $>10^6$ events above 10^{17} eV.
- Detector systematics are understood and being reduced.

Physics Results

- Energy spectrum
  - Statistically significant change in spectral index near GZK region.
- Mass composition
  - Hybrid elongation rate sugests mass mixture.
- Arrival direction anisotropy
  - New data do not favor previous claims of correlations with local AGNs
  - Still good evidence for correlations with mass distribution